

Optimal load distribution estimation for fault location in electric power distribution systems

YOUSSEF MENCHAFOU¹, MUSTAPHA ZAHRI², MOHAMED HABIBI², HASSANE EL MARKHI¹

¹Laboratory of Signals, Systems and Components
Sidi Mohamed Ben Abdellah University, Fez, Morocco
e-mail: {youssef.menchafou/hassane.elmarkhi}@usmba.ac.ma

²Laboratory of Electrical Engineering and Energy Systems
Ibn Tofail University, Kenitra, Morocco
e-mail: mustapha.zahri@gmail.com, mohamed.habibi@hotmail.com

(Received: 19.04.2016, revised: 19.07.2016)

Abstract: Accurate fault location in an electric power distribution system (EPDS) is important in maintaining system reliability. Diverse methods have been proposed in the past. These methods whither require measurements at each load point or use single-step loads compensation, which is hardly available in practical uses. In this paper, a simple technique to bypass the load problems is proposed. The method requires calculating an optimal load distribution using the total load seen from the substation (The rated power of distribution transformers) and the network topology. The optimal load distribution is used as a fictive distribution to replace the real unknown one in fault location (FL) algorithms. The effectiveness of the proposed technique is demonstrated using a mathematical formulation first, and next, by several simulations with a classic iterative fault location algorithm. The test results are obtained from the numerical simulation using the data of a distribution line recognized in the literature.

Key words: electric power distribution systems, fault location, fictive load distribution, load variation

1. Introduction

Power distribution systems play important roles in modern society. When distribution system outages occur, speedy and precise fault location is crucial in accelerating system restoration, reducing outage time and significantly improving system reliability. This allows consequently improving the quality of services and customer satisfaction. Nevertheless, Owing to the expansion of distribution networks, their radial topology, and the existence of short and heterogeneous lines and intermediate loads, it is very difficult and complicated to locate the fault in these networks.

In the past, various fault location algorithms have been developed. Novosel et al. (1998) make use of apparent impedance, defined as the ratio of selected voltage to current based on

fault type and faulted phases, to locate faults in [1]. In [2], Das (1998) locates the faulted section and next the distance to the fault in this section is calculated. Yang and Springs (1998) propose a fault location method which corrects the fault resistance effects in [3]. The method proposed by Das et al. (2000) in [4] used the fundamental frequency voltages and currents measured at a line terminal before and during the fault. In [5] the method proposed by Saha and Rosolowski (2002) estimates the fault location by comparing the measured impedance with the calculate feeder impedance assuming faults each section line. Choi et al. (2004) locating faults by solving a quadratic equation resulting from the direct circuit analysis in [6]. Senger et al. (2005) in [7] proposed a method that was based on measurement provided by intelligent electronics Devices (IEDs). In [8] Kim et al. (2007) estimated fault location on distribution feeders using Power Quality monitoring data. An extended fault location method for generalized distribution systems is presented in [9] by Salim et al. (2009). A way to optimally place faulted circuit indicators along the feeder is developed in [10] by Almeida et al. (2011). Methods to reduce and eliminate the uncertainty about the fault location are discussed by authors of [11, 12] (2012). In [13], Sadeh et al. (2013) suggested a new algorithm for radial distribution systems using modal analysis. Wanjing et al. presented a novel method based on two types of fault location approaches using line to neutral or line to line measurement at substation in [14] (2014). In [15], Zahri et al. (2014) proposed a new hybrid method based on ANN and Apparent impedance calculation to determinate the faulty section of line. A reduced algorithm for fault location in EPDS is suggested by Zahri et al, in [16] (2015), utilizing voltages and currents measurement only at the sub-station as input data to calculate the fault current, and therefore, avoid the iterative aspect of the classic algorithm for single line to ground fault location and reduce its computational charge.

However, fault location approaches for transmission lines are generally not applicable to distribution systems, because of their inherent characteristic, such as unbalance and lack of measuring meters in each load point.

According to literature review, it's shown that existing fault location methods require iterative short circuit analysis or iteratively calculating voltages and currents at different segments. Nevertheless, individually these methods do not fully consider the characteristics of distribution systems (unbalanced operation, presence of intermediate loads, laterals, and time-varying load profile), which significantly affect their performance. Except for [6] and [9], the previously cited methods do not account for the time-varying load profile. This intrinsic characteristic of EPDS has a detrimental effect on the fault locators' accuracy, since the load data during the fault period is a required input for any impedance-based method. The approach described in [6, 9] uses a single-step compensation of loads, which requires measurements at each load point. However, these measurements are hardly available in practical EPDS.

Considering the limitations mentioned previously. In this paper, a mathematical development is presented to determinate the optimal load distribution. It is considered as an imaginary distribution, calculated using the total load seen from the substation and the network topology. To show the technique performances, a comparison is performed between different load distributions using a fault location algorithm recognized in literature.

The remainder of this paper is organized as follows: the optimal load distribution formulation and the iterative fault location algorithm are presented in Sections 2 and 3 respectively, the test results are shown in Section 4, whereas the conclusion of this work is presented in Section 5.

2. Optimal load distribution formulation

The load demand in EPDS depends on the consumer type (residential, industrial or commercial) and may vary with many factors. Also, impedance-based fault-location methodologies are dependent on the system loading during the fault. If the system has a different load profile during the algorithm execution, this will lead to errors [9]. The minimum errors correspond to the optimal load profile (distribution).

In order to determinate the optimal load distribution, the following mathematical development is done using a simplified modeling of a distribution network illustrated in Figs. 1 and 2. The fault location is calculated using the sending-end voltages and currents, line parameters and load current. Consequently, the errors on the fault location are computed as a function of load distribution variation.

2.1. Pre-fault mathematical development

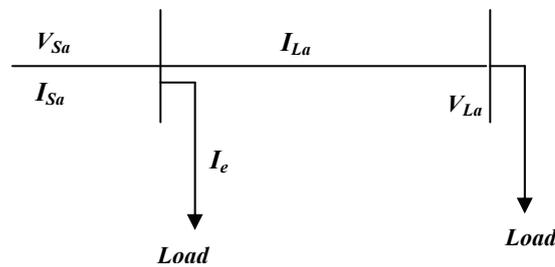


Fig. 1. Pre-fault simplified distribution network modeling

where: I_{Sa} is the phase a pre-fault sending-end current; V_{Sa} is the phase a pre-fault sending-end voltage; I_e is the first pre-fault load current; Z_a is the line impedance; V_{La} is the phase a pre-fault voltage at the end of the line section.

Considering the system illustrated in Fig. 1, the following equations can be obtained:

$$V_{Sa} = Z_a \cdot l \cdot I_{La} + V_{La}, \quad (1)$$

$$V_{Sa} - V_{La} = Z_a \cdot l \cdot I_{La}, \quad (2)$$

$$V_{Sa} - V_{La} = Z_a \cdot l \cdot (I_{Sa} - I_e). \quad (3)$$

Since all the loads after the section illustrated in Fig. 1 are represented as one equivalent load Z_e , and the total current dispatched to it is I_{La} , Z_e is then computed by Equation (4):

$$Z_e = \frac{V_{Sa}}{I_{Sa} - I_e} - (Z_a \cdot l). \quad (4)$$

2.2. Mathematical development during the fault

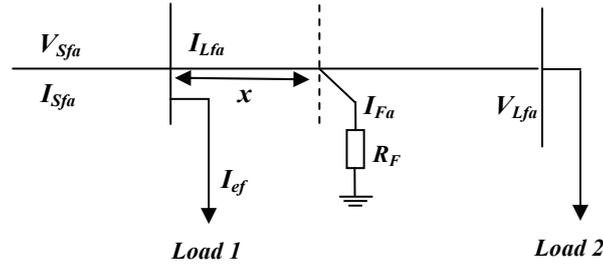


Fig. 2. During-fault simplified distribution network modeling

where: I_{Sfa} is the phase a sending-end current during the fault; V_{Sfa} is the phase a sending-end voltage during the fault; I_{ef} is the first load current during the fault; Z_a is the line impedance; V_{Lfa} is the phase a voltage at the end of the line during the fault; I_{Fa} is the phase a fault current.

Referring to Fig. 2, the following equations can be obtained:

$$\begin{cases} V_{Sfa} = Z_a \cdot x \cdot I_{Lfa} + R_F \cdot I_{Fa}, \\ R_F \cdot I_{Fa} = V_{Lfa} + Z_a \cdot (l - x) \cdot (I_{Lfa} - I_{Fa}), \end{cases} \quad (5)$$

$$\begin{cases} V_{Sfa} - R_F \cdot I_{Fa} = Z_a \cdot x \cdot (I_{Sfa} - I_{ef}), \\ R_F \cdot I_{Fa} - V_{Lfa} = Z_a \cdot (l - x) \cdot (I_{Sfa} - I_{ef} - I_{Fa}), \end{cases} \quad (6)$$

$$\begin{cases} R_F = \frac{V_{Sfa} - Z_a \cdot x \cdot (I_{Sfa} - I_{ef})}{I_{Fa}}, \\ x = \frac{V_{Sfa} - V_{Lfa}}{Z_a \cdot I_{Fa}} - \frac{I_{Sfa} - I_{ef} - I_{Fa}}{I_{Fa}} \cdot l. \end{cases} \quad (7)$$

Furthermore, the load voltage during fault can be obtained by (8):

$$\begin{aligned} V_{Lfa} &= Z_e \cdot (I_{Sfa} - I_{ef} - I_{Fa}), \\ V_{Lfa} &= \left(\frac{V_{Sa}}{I_{Sa} - I_e} - Z_a \cdot l \right) \cdot (I_{Sfa} - I_{ef} - I_{Fa}). \end{aligned} \quad (8)$$

Using Equations (7) and (8), the fault distance can be estimated by (9):

$$x = \frac{1}{Z_a \cdot I_{Fa}} \cdot \left(V_{Sfa} - (I_{Sfa} - I_{ef} - I_{Fa}) \cdot \left(\frac{V_{Sa}}{I_{Sa} - I_e} \right) \right). \quad (9)$$

From (9) it is possible to obtain the fault distance from the parameters of the system: the fault current, the sending-end pre-fault voltage and the sending-end during-fault voltage. However, the important parameter is the load current since its variation allows to determinate the optimal errors, and therefore, estimates the optimal load distribution.

3. Iterative fault location algorithm

After determination of the optimal load distribution using the mathematical development, it's necessary to test the reliability of the technique by simulations. To reach that, the iterative fault location algorithm presented next is used [15, 17]:

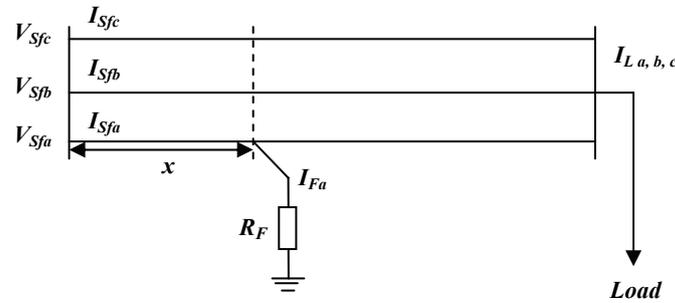


Fig. 3. Single-phase-to-ground fault modeling

Referring to the single line-to-ground fault illustrated in Fig. 3, the sending-end voltage during the disturbance is given by (10):

$$V_{Sfa} = V_{Fa} + x \cdot (Z_{aa} \cdot I_{Sfa} + Z_{ab} \cdot I_{Sfb} + Z_{ac} \cdot I_{Sfc}). \quad (10)$$

Supposing the fault impedance strictly resistive and constant, (10) may be expanded into its real and imaginary parts:

$$\begin{bmatrix} V_{Sfar} \\ V_{Sfai} \end{bmatrix} = \begin{bmatrix} M_{1a} & I_{Fmr} \\ M_{2a} & I_{Fmi} \end{bmatrix} \begin{bmatrix} x \\ R_{Fa} \end{bmatrix}. \quad (11)$$

From (11), the fault distance may be calculated as a function of the sending-end voltages and currents, as well as the line parameters:

$$\begin{bmatrix} x \\ R_F \end{bmatrix} = \frac{1}{M_{1a} \cdot I_{Fai} - M_{2a} \cdot I_{Far}} \begin{bmatrix} I_{Fai} & -I_{Far} \\ -M_{2a} & M_{1a} \end{bmatrix} \begin{bmatrix} V_{Sfar} \\ V_{Sfai} \end{bmatrix}, \quad (12)$$

where the subscript indices r and i represent, respectively, the variables real and imaginary parts, the variables are as follows: V_{Sfa} is the phase a sending-end voltages (in volts); x is the fault point to local bus distance (in kilometers); I_{Fa} is the fault current (in amperes).

Also, M_{1m} and M_{2m} are defined in (13) and (14)

$$M_{1m} = \sum_k (Z_{mkr} \cdot I_{Skr} - Z_{mki} \cdot I_{Ski}), \quad (13)$$

$$M_{2m} = \sum_k (Z_{mkr} \cdot I_{Ski} - Z_{mki} \cdot I_{Skr}), \quad (14)$$

where k indicates the phases a , b and c ; Z_{mk} is the impedance between phase m and k [Ω/km]; I_{Sk} is the phase k sending-end current (in amperes).

The fault distance is then estimated by (15):

$$x = \frac{I_{Fai} \cdot V_{Sfar} - I_{Far} \cdot V_{Sfai}}{M_{1a} \cdot I_{Fai} - M_{2a} \cdot I_{Far}}. \quad (15)$$

4. Tests and results

4.1. Optimal load distribution formulation test

First, the optimal load distribution formulation test is done for determining the optimal load distribution. The test's system is constituted by two sections of a 20 kV distribution line. Their lengths are 2 km and 1 km, respectively. The currents of the first load I_{ef} and the second load ($I_{af} - I_{ef}$) are varied, since they are complementary. Based on this variation the errors on the fault distance are calculated and the minimum errors correspond to an optimal load pair (load 1, load 2).

On the Fig. 4, the errors on fault distance varies according to the current of the first load I_{ef} between " $I_{af}/100$ " and " I_{af} " (with I_{af} is the total current during the fault), since $I_{af} = 239.1857$, I_{ef} varies between [2.3919-239, 1857].

To determinate the optimal load distribution, or in other words the value of I_{ef} which gives the minimum errors, the module of the errors in Fig. 4 is computed, the results are illustrated in Fig. 5.

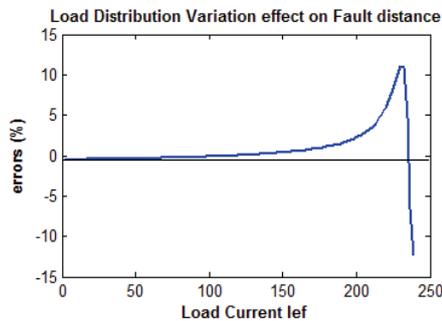


Fig. 4. Errors on the fault distance according to the current of the first load

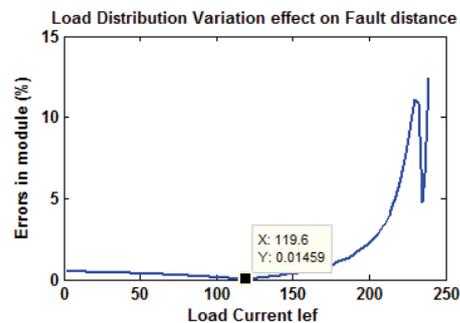


Fig. 5. Module of errors on the fault distance according to the current of the first load

On the Fig. 5, it can easily be seen that the error is null for the value “ $I_{ef} = 119.6$ ” which represents 50% of the current I_{ef} , since $I_{ef}/2 = 239.1857 / 2 = 119.59285$.

Therefore, from the figures below, we can conclude that:

- The Load distribution variation influences the accuracy of the fault location methods.
- The optimal load distribution which gives the minimum errors is around 50% of the total load. Thus, the optimal load distribution is the pair (50%, 50%) this pair can be called “the balanced loads distribution”.

4.2. Application for the iterative fault location algorithm

To verify performances of this method, we have conducted several simulations using data from a distribution system recognized in literature [18].

The system that we have studied is a part of the underground distribution network. It is a line from 20 KV distribution network of total length 22.5 km, composed of 6 sections of different lengths and simulated using distributed parameter line model as shown in Table 1.

Table 1. Studied sections of lines parameters

Input voltages [KV]	$V_S = 11.547, U = 20$
R_F [ohms]	10
line impedance [ohms/km]	$Z_1 = 0.56 + j0.831, Z_0 = 0.845 + j 2.742$
line section length[km]	$l_1 = 2.4; l_2 = 4; l_3 = 4; l_4 = 4; l_5 = 4.1; l_6 = 4$

Using Matlab [19] as simulation tool, 26 fault cases are simulated at different FL between 0-100%, for fault resistance $R_F = 10 \Omega$ and for different load distributions as explained in Table 2:

- balanced loads distribution,
- increasing loads distribution,
- decreasing loads distribution,
- total load at the first load point,
- total load at the last load point.

Table 2. Different load distributions

Load distribution (KVA) for each bus	1	2	3	4	5	6
Balanced loads distribution	15	15	15	15	15	15
Increasing loads distribution	0.1	5	10	20	25	29.9
Decreasing loads distribution	29.5	25	20	10	5	0.1
Total load at the first load point	89.5	0.1	0.1	0.1	0.1	0.1
Total load at last load point	0.1	0.1	0.1	0.1	0.1	89.5

The fault distance is calculated for each case using the currents and voltages at the input of the line. The sending-end currents and voltages are computed considering a real load distribution. The errors on fault location obtained using the real load distribution are compared with

those obtained using the others as imaginary load distributions in order to determinate the optimal load distribution.

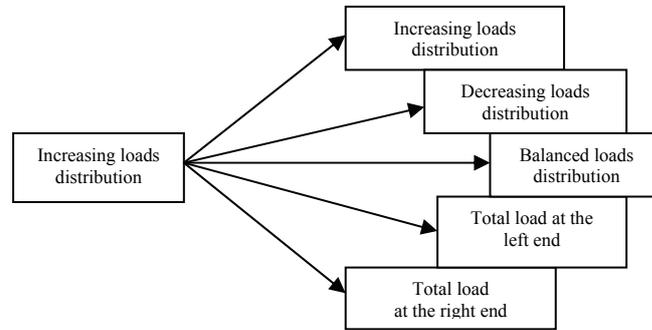


Fig. 6. Example of simulation procedure

The Fig. 6 above illustrates an example of this comparison, the increasing loads distribution is the real distribution, and the others are considered fictive.

To analyze the load distribution variation effect on the fault location, and to confirm the results of the optimal load distribution formulation, the cross distributions in Figs. 7(a-d) are classified according to their errors.

Fig. 7(a) illustrates some obtained test results, for the simulation system presented above, with the balanced loads distribution as real distribution during the fault, compared with the five other distributions used to compute the fault location as fictive distributions.

The increasing loads distribution is used as real distribution in Fig. 7(b), from the comparison of the real distribution with the other fictive distributions used as input of the fault location algorithm. The simulation of the decreasing loads distribution in comparison with the other distributions is plotted in Fig. 7(c).

To confirm the previous results, a random distribution is simulated in Fig. 7(d). The classification obtained from these simulations is presented in Table 3.

Table 3. Load distributions classification

Fictive load distribution	Real load distribution			
	Balanced loads distribution	Increasing loads distribution	Decreasing loads distribution	Random distribution
Balanced loads distribution	+	+	+	+
Increasing loads distribution	+	+	-	-
Decreasing loads distribution	-	-	+	+
Total load at the first point	-	-	+	-
Total load at the last point	+	+	-	-
Random distribution	-	-	-	+

From load distribution classification below, it can be concluded that the best results are, always, obtained using the real distribution to compute the fault location. Nevertheless, the

real distribution is not available in practical networks, because it requires knowledge about measurements at each load point which is hardly available in practical EPDS.

However, it can be seen that the maximum errors for the balanced loads distribution are less than 0.04% for all the distributions. Thus, this distribution is the optimal load distribution which proves the result of the optimal load distribution formulation.

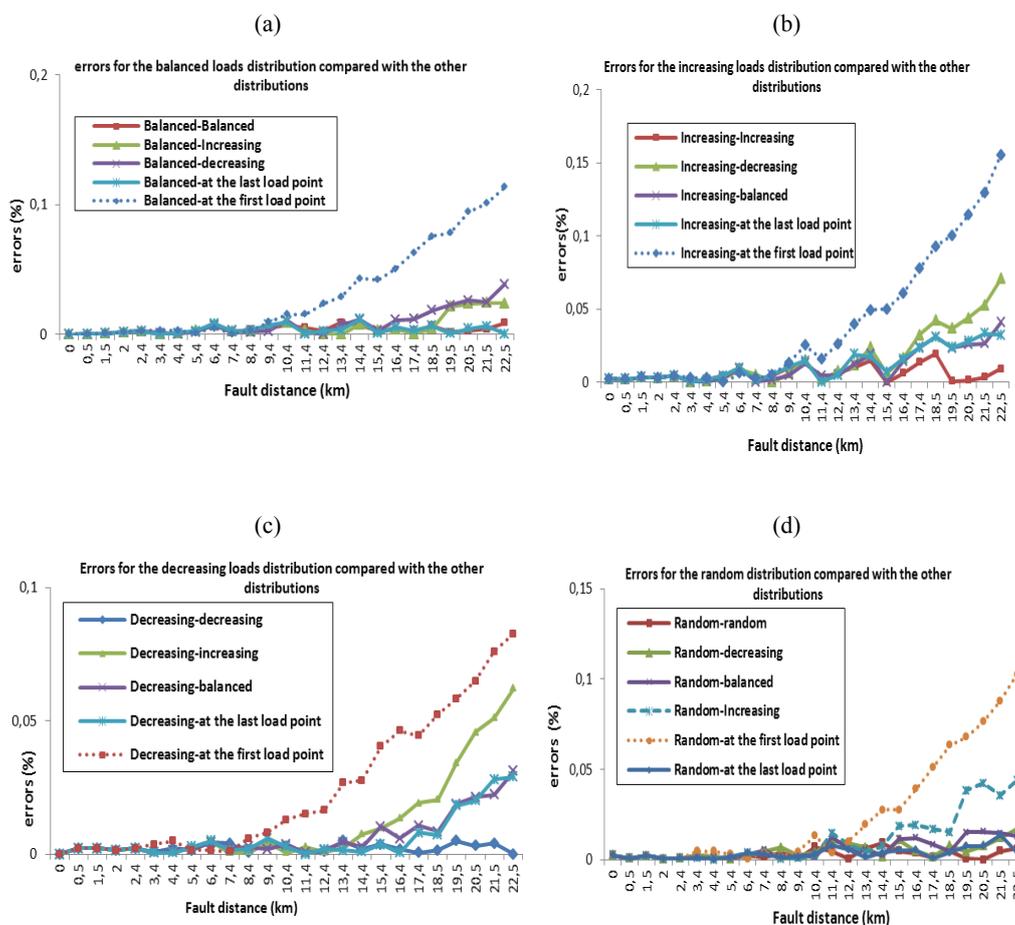


Fig. 7. Errors for each real load distribution compared with the other fictive load distributions.

6. Conclusions

A novel technique to estimate the optimal load distribution in fault location algorithms for Electrical Power Distribution Systems has been presented in this paper. Voltage and current measurements at substation are utilized to estimate the total load during the fault. The total

load is divided fairly on all load points considering network topology. Most of the techniques found in the literature are focused on measurement at each load point or based on load compensation which is hardly available in practical EPDS. The difficulties that arise when considering a load distribution known to locate faults on practical EPDS were highlighted in this paper.

The performances of this technique are verified by several tests simulating 26 cases of single phase to ground faults for different cross load distributions.

Simulation results and mathematical formulation show that the balanced loads distribution can be considered as a fictive optimal distribution in fault location algorithms thanks to its estimation simplicity and its robust effectiveness.

References

- [1] Novosel D., Hart D., Myllymaki J., *System for locating faults and estimating fault resistance in distribution networks with tapped loads*, U.S. Patent 5839093 (1998).
- [2] Das R., *Determining the locations of faults in distribution systems*, Doctoral thesis. University of Saskatchewan, Saskatoon, Canada (1998).
- [3] Yang L., Springs C., *One terminal fault location system that corrects for fault resistance effects*, US Patent number 5,773,980 (1998).
- [4] Das R., Sachdev M.S., Sidhu T.S., *A fault locator for radial sub-transmission and distribution lines*, IEEE Power Engineering Society Summer Meeting, Seattle, WA, USA, July 16-20 (2000).
- [5] Saha M., Rosolowski E., *Method and device of fault location for distribution networks*, US Patent number 6,483,435 (2002).
- [6] Choi M.S., Lee S., Lee D., Jin B., *A new fault location algorithm using direct circuit analysis for distribution systems*, IEEE Trans. Power Syst., vol. 19, no. 1, pp. 35-41 (2004).
- [7] Senger E., Manassero J., Goldemberg C., Pellini E., *Automated fault location system for primary distribution networks*, IEEE Trans. Power Del., vol. 20, no. 2, pp. 1332-1340 (2005).
- [8] Kim J., Baran M., Lampley G., *Estimation of fault location on distribution feeders using PQ monitoring data*, IEEE Power Engineering Society General Meeting, Tampa, FL (2007).
- [9] Salim R.H., Resener M., Filomena A.D., Rezende Caino d'Oliveira K., Bretas A.S., *Extended Fault-Location Formulation for Power Distribution Systems*, IEEE Transactions on Power Delivery, vol. 24, no. 2 (2009).
- [10] d'Almeida M.C., Costa F.F., Xavier-de-Souza S., Santana F., *Optimal placement of faulted circuit indicators in power distribution systems*, Electr. Power Syst. Res., vol. 81, no. 2, pp. 699-706 (2011).
- [11] Krishnathavar R., Ngu E.E., *Generalized impedance-based fault location for distribution systems*, IEEE Transactions on Power Delivery, vol. 27, no. 1, pp. 449-451 (2012).
- [12] Avendano-Mora M., Milanovic J.V., *Generalized formulation of the optimal monitor placement problem for fault location*, Electr. Power Syst. Res., vol. 93, no. 12, pp. 120-126 (2012).
- [13] Sadeh J., Bakhshizadeh E., Kazemzadeh R., *New fault location algorithm for radial distribution systems using modal analysis*, Int. J. Electr. Power Energ. Syst., vol. 45, no. 1, pp. 271-278 (2013).
- [14] Wanjing X., Yuan L., *Novel fault location methods for ungrounded radial distribution systems using measurements at substation*, Electric Power Systems Research, vol. 106, pp. 95-100 (2014).
- [15] Zahri M., Menchafou Y., El Markhi H., Habibi M., *ANN and Impedance Combined method for Fault Location in Electrical Power Distribution Systems*, International Journal of Electrical Engineering and Technology, vol. 5, no. 9, pp. 29-38 (2014).
- [16] Zahri M., Menchafou Y., El Markhi H., Habibi M., *Simplified method for single line to ground-fault location in electrical power distribution systems*, International Journal of Electrical and Computer Engineering, vol. 5, no. 2, pp. 246-255 (2015).

-
- [17] Filomena A.D., Resener M., Salim R.H., Bretas A.S., *Fault location for underground distribution feeders: An extended impedance-based formulation with capacitive current compensation*, *Electr. Power and Energy Syst.*, vol. 31, pp. 489-496 (2009).
- [18] Filomena A.D., Resener M., Salim R.H., Bretas A.S., *Distribution systems fault analysis considering fault resistance estimation*, *Electr Power and Energy Syst.*, vol. 33, pp. 1326-1335 (2011).
- [19] Matlab Help Manual, The Mathworks Inc. (2009).